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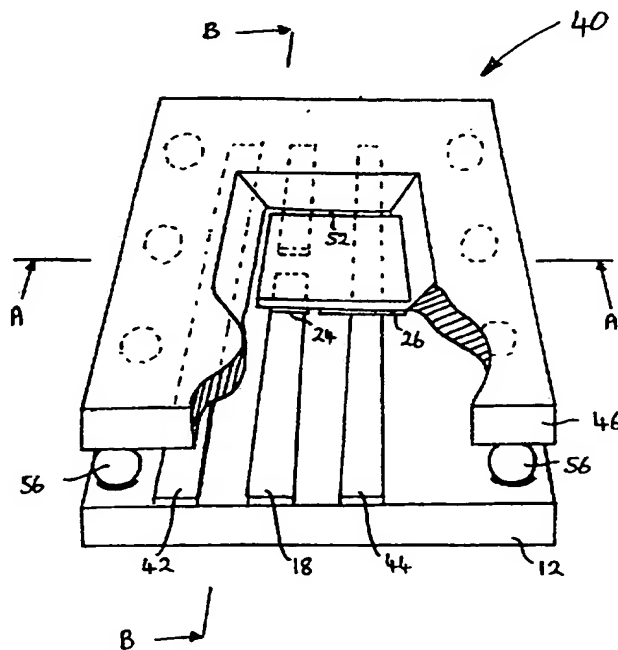
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(54) Abstract Title
Electrical switch

(57) An electrical switch 40 comprises: electrical contacts 18, (20, fig 1) and 24 and an actuator 26 for moving the contacts relative to each other between an open state and a closed state. The actuator 26 includes a deformable member 14, preferably a cantilever, which includes a material 26, preferably piezoelectric, which is able to undergo a dimensional change in response to an electric field applied thereacross for moving the contacts relative to each other. The deformable member 14 may be microfabricated from a first substrate 46 which is joined to a second substrate 12 including at least some of the contacts 18 and (20, fig 1) to form an assembly.



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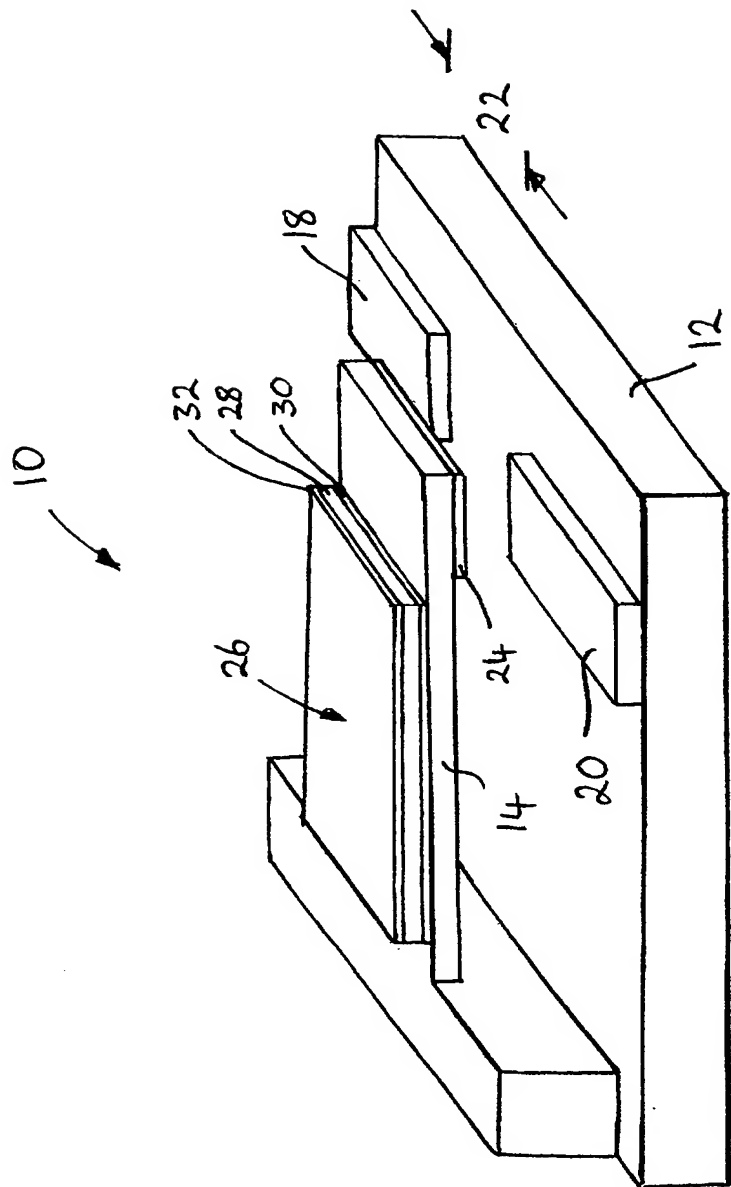


Figure 1.

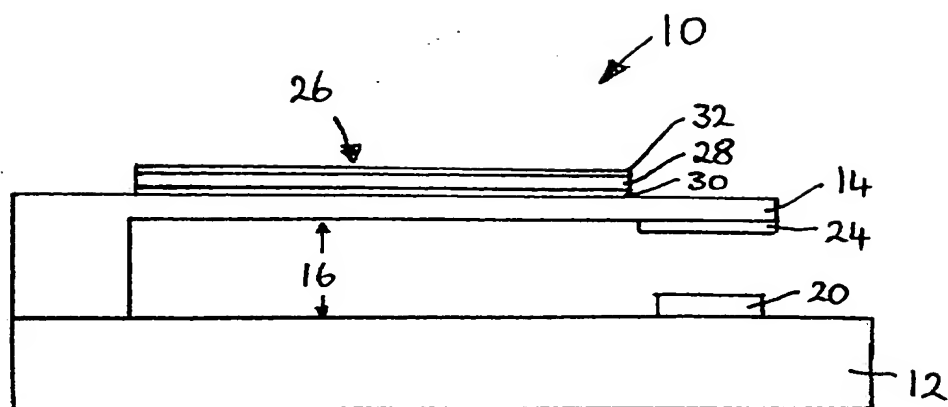


Figure 2.

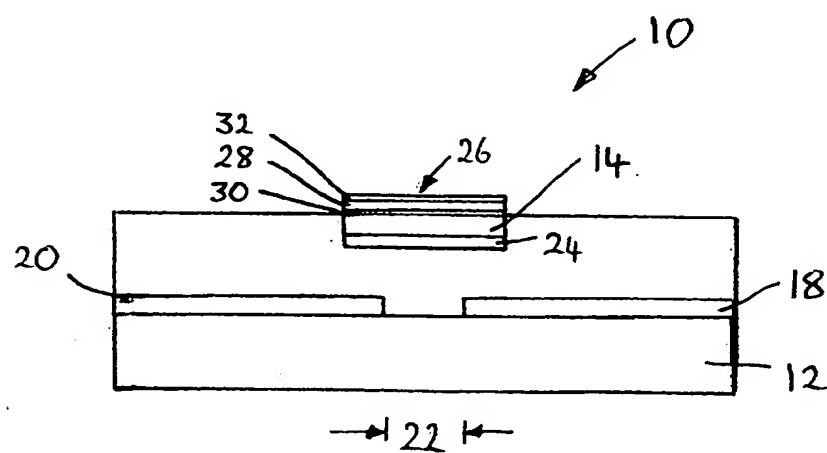


Figure 3.

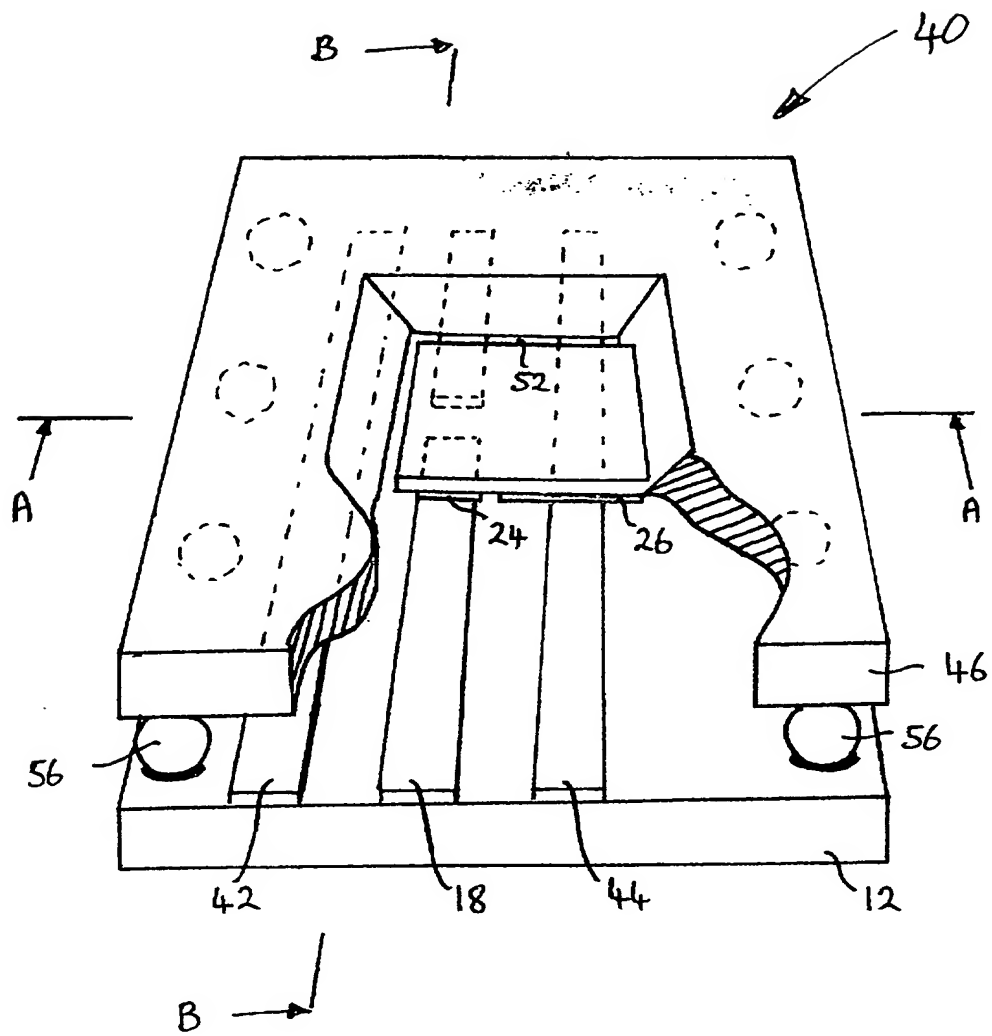


Figure 4.

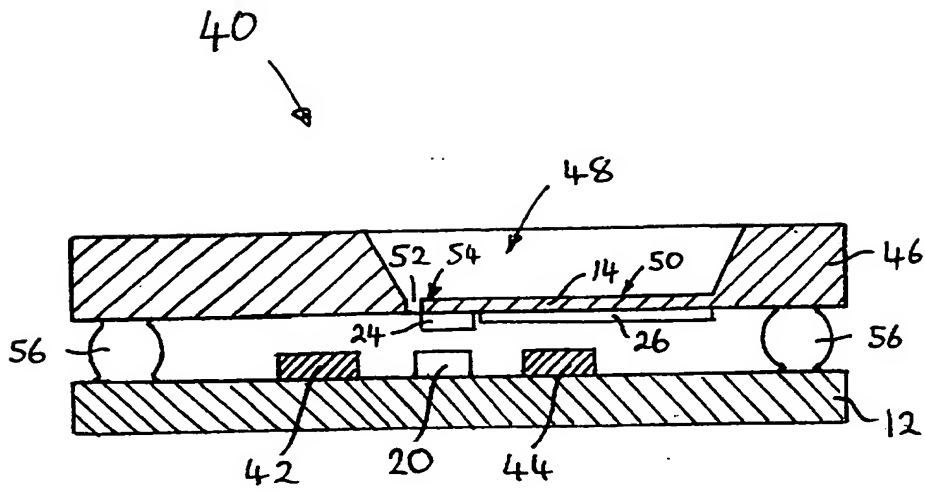


Figure 5

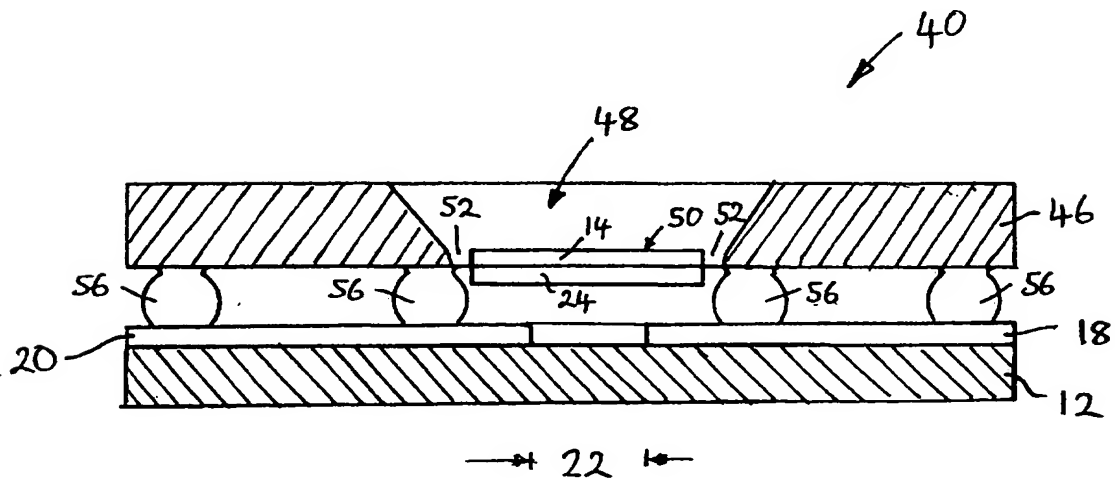


Figure 6.

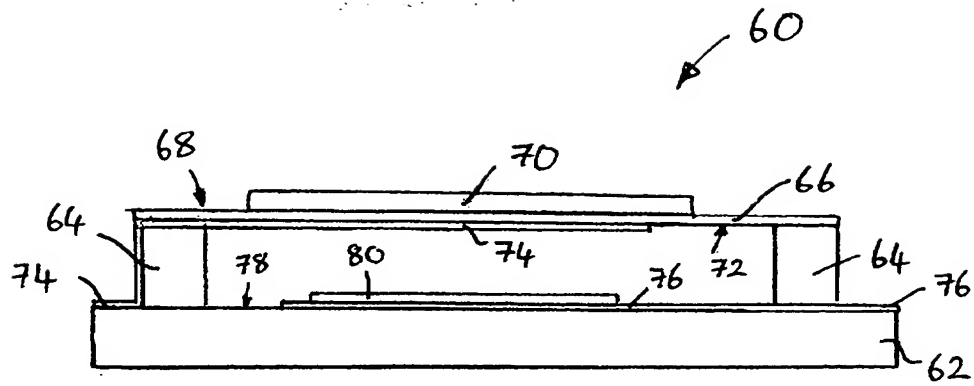


Figure 7.

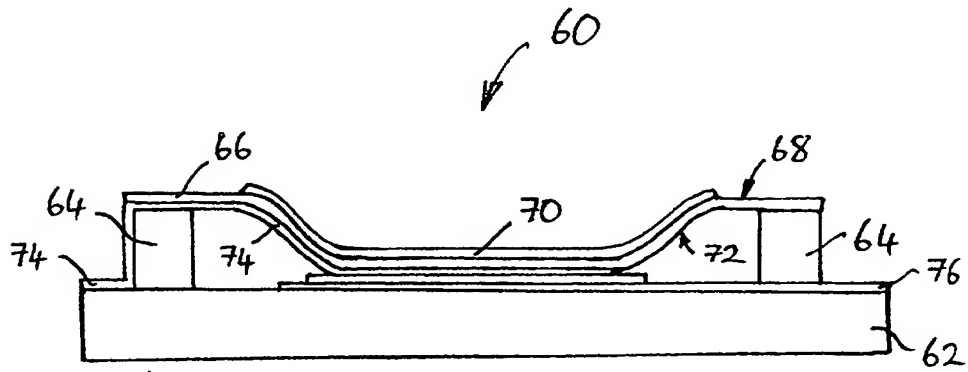


Figure 8.

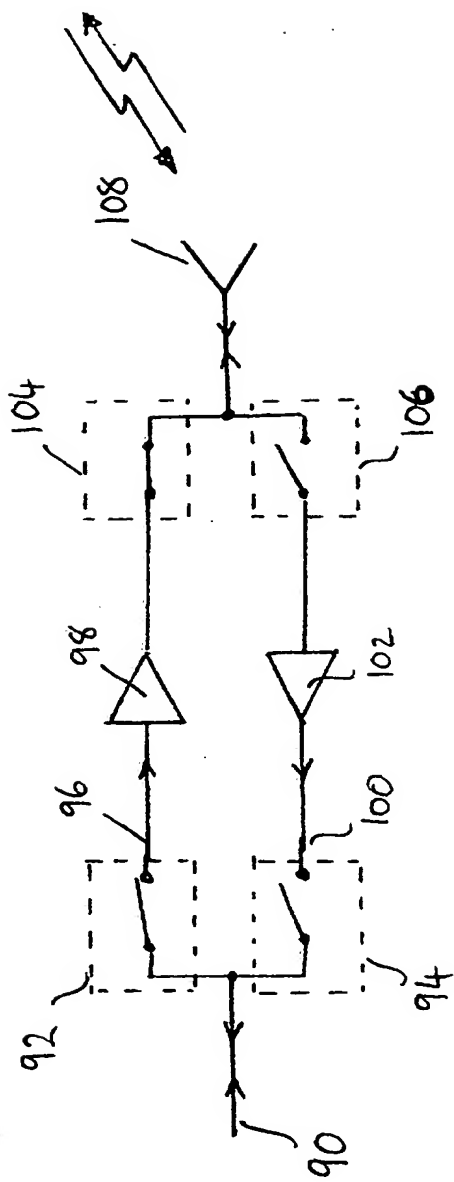


Figure 9.

ELECTRICAL SWITCHES

This invention relates to electrical switches and is more especially, although not exclusively, concerned with switches for switching microwave signals in for example phased array antenna systems as used in communications and radar applications.

5 Switching of microwave signals is necessary in many applications such as cellular communication systems, satellite direct broadcast, terrestrial broadcast and systems which utilise phased array antenna systems. For example, in the amplification stages of a phased array system for radar or communication, microwave power is switched through a power amplifier during transmission and through a low noise amplifier during
10 reception.

Another example of switching of microwave signals is in steering a beam produced by a phased array antenna using time delay phase shifting in which microwave signals are switched along transmission lines of different lengths. Each transmission line leading up
15 to an antenna element of the array is divided into a number of sections, each section having a relatively short transmission length and a relatively long transmission length. A switch is provided for each section such that a microwave signal can be switched to be transmitted through either the short length or the long length. By selectively operating the switches along the transmission line, its transmission length can be varied thus
20 varying its transmission time and thereby introducing a phase delay to the microwave signal. A beam produced by the array can be steered by controlling the phase delays in a number of such lines.

It is known to switch microwave signals using solid state switches based on MESFETs (Metal Semiconductor Field Effect Transistor) or PIN diodes which can be connected in series or in shunt with the transmission line. Although solid state switches can provide rapid switching times of the order of a few nanoseconds problems exist with such switches. Typically they cause a loss of 0.5 to 2 dB for signals in the X-Band (8-12GHz), and due to their non-linear characteristics they exhibit power compression characteristics at relatively low power levels (of the order 27-30 dBm for MESFETs). As a consequence the use of solid state switches is limited to applications where significant losses can be tolerated and to low power applications. Furthermore switches based on diodes consume a relatively high amount of d.c. power, typically of the order of 20mA per diode which can amount to an appreciable power consumption in applications such as phased array antennas where several thousand such switches may be required.

It is also known to switch microwave signals using electrostatically actuated mechanical switches. One such switch comprises a polysilicon cantilever beam which is supported above a substrate such that a conductor at the free end of the beam overlays a gap in a transmission line provided on the substrate. The substrate and cantilever are provided with complementary electrodes which are used to actuate the switch. When an actuating voltage is applied across the electrodes the electrostatic force of attraction between the electrodes causes the cantilever to bend such that the conductor bridges the gap in the transmission line thereby closing the switch. Electrostatic switches have also been proposed which comprise a membrane which is supported by a peripheral frame. The switch is activated by the electrostatic force of attraction between the membrane, which may be metallic, and a corresponding electrode on the substrate. Although electrostatic

switches, due to the physical separation of the contacts, provide a higher electrical isolation (up to 120dB) compared with that of solid state switches, they require a high operating voltage, typically of the order of 20 to 100V, making them TTL (Transistor Transistor Logic) and CMOS (Complementary Metal Oxide Semiconductor) incompatible.

The present invention has arisen in an endeavour to provide an electrical switch which is capable of switching microwave signals and which at least in part overcomes the limitations of the known switches.

According to the present invention an electrical switch comprises: an actuator for moving contacts relative to each other between an open state and a closed state characterised in that the actuator comprises a material which undergoes a dimensional change in response to an electric field applied across the material. A particular advantage of a switch in accordance with the invention is that it only requires low voltages, of the order of a few volts, to actuate the switch making it compatible with TTL and CMOS logic. Being a simple mechanical device it provides a high isolation (typically 25dB at 50GHz) in the open state and a low-loss contact typically in the order of about 0.1dB when switching signal over a frequency range of d.c. to 50 GHZ. Furthermore a switch according to the invention is relatively simple in construction and so can be fabricated in miniature form having a typical dimension of 2mm x 2mm. It is also robust and reliable.

Preferably the material comprises an electro-strictive material and is most preferably a piezoelectric material such as lead zirconate titanate (PZT). A particular advantage in

using a piezoelectric material is that its dimensional change is substantially linear with applied electric field. Preferably the actuator comprises a film of said material and two or more electrodes for applying an electric field thereto. The piezoelectric film or similar may be deposited in layered form to maximise deflection while minimising the electric field. The field applied to each layer may also be applied in opposite directions to maximise deflections.

Advantageously the switch further comprises a base carrying one of the electrical contacts and a support member carrying the second contact; wherein the actuator is coupled to said support member such that a dimensional change in the actuator causes a deformation of the support member to open or close the switch. In one embodiment the support member is planar in form such as a cantilever. Alternatively the support member comprises a strip supported at opposite edges or a membrane.

In a preferred embodiment the contact on the base or support member is configured such as to provide an electrical path having a break therein and the corresponding contact on the support member or base is configured to electrically bridge said break when the switch is in a closed state. Alternatively the switch further comprises a dielectric layer on one of said pair of contacts such that an electrical signal is capacitively coupled between said contacts when the switch is in a closed state.

In a particularly preferred embodiment the support member and the base are fabricated separately and then joined together to provide an assembly. Advantageously the support and base comprise different materials such as silicon and gallium arsenide respectively.

Preferably the support member and/or base are fabricated by micromachining.

In a particularly preferred arrangement the base comprises an integrated surface to which the support member is bonded by, for example, flip chip solder bonding.

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According to a further aspect of the invention an integrated circuit incorporates one or more switches as described above.

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Preferably such switches are used in a phased array antenna system for transmitting and/or receiving beams of microwave radiation. For example they may be used to switch different transmission lengths to provide variable phase delays. Alternatively they may be used to switch an antenna between transmission and reception modes or to switch between a transmission antenna or a reception antenna.

15

Phased array antennas are known in which a common antenna is connected to a circulator which, in turn, is connected to both the power amplifier and the low noise amplifier. Replacing the circulator with a plurality of switches according to the invention provides improved isolation of the low noise amplifier and, due to reduced insertion loss, less waste of transmitted power and a reduced overall noise figure.

20

According to yet a further aspect of the invention a phased array antenna incorporates one or more electrical switches as described above.

Whilst the switch of the present invention is primarily intended for switching electrical

signals it is also envisaged that the switch can be used to switch other media such as for example optical signals. Thus according to a further aspect of the invention there is provided a switch designed to be operated by an electro-strictive effect.

- 5 In order that the invention may be better understood three switches in accordance with the invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a schematic isometric representation of a cantilever switch;

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Figure 2 is a side view of the cantilever switch of Figure 1;

Figure 3 is an end view of the cantilever switch of Figure 1;

- 15 Figure 4 is an isometric partial cut away of second cantilever switch in accordance with the invention;

Figure 5 is a cross section along the line AA of the switch of Figure 4;

- 20 Figure 6 is a cross section along the line BB of the switch of Figure 4;

Figure 7 is a schematic representation of a membrane switch in accordance with the invention in an "open" state;

Figure 8 shows the membrane switch of Figure 7 in a "closed "state; and

Figure 9 is a schematic representation of a switching arrangement for use in a phased array antenna system.

5

A switch in accordance with a first embodiment of the invention is shown in Figures 1, 2 and 3 which show a single pole single throw (SPST) cantilever switch 10 which comprises an electrically insulating base or substrate 12 upon which a cantilever 14 is mounted in fixed relation and is separated from the substrate 12 by a gap 16. The
10 substrate 12 comprises a material which is insulating at the frequency of the signals the switch is intended to switch. Thus when the switch is intended for switching microwave signals, such as for example for frequencies up to 50 GHZ, the substrate comprises a material having a low loss at these frequencies such as for example gallium arsenide (GaAs), gallium nitride (GaN), aluminium nitride (AlN), sapphire, quartz,
15 silicon:germanium or a ceramic material such as alumina or a low temperature co-fired ceramic (LTCC). For operations with lower frequency signals the substrate preferably comprises silicon (Si). The cantilever 14 can comprise the same material as the substrate 12 though for ease of manufacture it is preferably made of silicon.

20 Upon the surface of the base 12 opposite the cantilever 14 there are provided electrically conducting tracks 18, 20 which are configured to form an electrically insulating gap 22 which is located under the cantilever 14. A complementary and opposing electrically conducting contact 24 is provided on the cantilever 14 such as to overlay the gap 22. The contact 24 is dimensioned such that when the switch is actuated, as described below,

it bridges the gap 22 between the conducting tracks 18, 20 and electrically connects the tracks 18, 20.

An actuator, generally denoted 26, is provided on an upper surface of the cantilever 14.

5 The actuator 26 comprises a film or thin layer of piezoelectric material 28, most preferably lead zirconate titanate (PZT), which is sandwiched between metallic electrode layers 30, 32. The actuator 26, more specifically the piezoelectric material layer 28, is coupled to the cantilever 14 such that deformation of the layer 28 will cause a corresponding deformation of the cantilever 14.

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In operation of the switch 10 when a potential difference is applied between the electrodes 30, 32 the resultant electric field across the piezoelectric film 28 causes its length to increase relative to the length of the cantilever 14 and this causes the cantilever 14 to bend in a direction towards the base 12. The bending of the cantilever 14 brings
15 the contacts 24 into electrical contact with the conducting tracks 18, 20, electrically bridging the gap 22 thereby "closing" the switch. Removal of the electric field allows the cantilever 14 to straighten and thus "opens" the switch. To cause the switch to "open" more rapidly the direction of the electric field can be reversed rather than being removed thereby causing the length of the piezoelectric layer to contract. It will be
20 appreciated that in alternative arrangements the actuator can be located elsewhere on the switch such as for example on the underside of the cantilever in which case it is operable to "close" the switch through a contraction in the length of piezoelectric layer. Furthermore it will be appreciated by those skilled in the art that alternative switch configurations can be readily devised which "open" on application of electric field and

“close” on its removal or reversal.

A cantilever switch in accordance with a second embodiment of the invention is shown in Figures 4, 5 and 6 which show a SPDT cantilever switch 40 for switching the signals from d.c to 50GHz. For consistency the same reference numerals are used to denote like parts to those of the switch of Figure 1 to 3.

The switch 40 and its method of construction is now described by way of reference to Figures 4, 5 and 6. The switch 40 is of hybrid construction in which the base 12 is of suitable low loss microwave substrate, most preferably GaAs, and the cantilever is made of silicon. On the GaAs substrate 12 the conducting tracks 18, 20, which preferably comprise gold, are deposited using a suitable method such as metal deposition evaporation, sputtering or plating up. The conducting tracks 18, 20 are flanked by coplanar parallel conducting tracks 42, 44 deposited in a like manner. The tracks 42, 44, which are unbroken, provide ground lines whilst the tracks 18, 20 provide the switchable signal line. Typically each of the tracks 18, 20, 42, 44 is approximately 50µm wide and spaced apart by approximately 60µm. The gap 22 between the tracks 18, 20 is of the order of 200µm which, in conjunction with a 5-11µm gap between the cantilever and the substrate 12, provides an electrical isolation in the “open” state of approximately 30dB.

20

The cantilever 14, which is of silicon, is fabricated separately to that of the GaAs substrate. The cantilever 14 is micromachined into a silicon substrate 46 by firstly etching downwards from the surface to create a rectangular pit 48 having sloping sides

and a thin bottom 50 of the order of $20\mu\text{m}$ thickness. A gap 52 is then etched around three of the edges of the bottom 50 to provide the cantilever 14 having a free end 54. In the context of this patent application micromachining is to be interpreted as meaning those processes which are used to create three dimensional structures at a μm scale such as for example those used in the fabrication of silicon based integrated circuits and include for example bulk chemical etching, vapour deposition, reactive ion beam sputter deposition/etching or milling, laser machining and ion implantation.

The contact 24 and electrode 30 are deposited on the planar surface of the cantilever 14 and a film 28 (typically this is of order $1\mu\text{m}$ thickness) of PZT deposited over the electrode 30. Most conveniently the PZT film is deposited by sol-gel (solvent-gel) deposition by spinning a layer of sol-gel over the planar surface of the substrate 46, sintering the substrate and then etching away unwanted areas of PZT. Although the actuator 26 can be provided on the upper surface of the cantilever it is preferred to provide it on the lower planar surface due to its ease of fabrication. Finally the second electrode 32 of the actuator 26 is deposited.

The switch 40 is finally assembled by joining the substrates 12 and 46 using flip chip solder bonding. This process provides good placement accuracy and height control by using solder bumps 56 which are located on respective metallic pads which are deposited when the tracks 18, 20, 42, 44 and electrode 32 are deposited.

The operation of the switch is identical to that described above such that electrical actuation of the PZT film 28 causes the cantilever 14 to bend thus bringing the metal

contact 24 into contact with the signal tracks 18, 20 thereby bridging the gap 22 and closing the switch 40. In the foregoing description the switch 40 is depicted as a discrete device, it will be appreciated however that a particular advantage of this switch 40 is that it can be readily fabricated as part of an integrated circuit in which the substrate 12 is the integrated circuit. In such an arrangement the conducting tracks 18, 20, 42, 44 and their interconnection to the circuit are deposited on the surface of the integrated circuit and the cantilever layer, which is fabricated separately, is then flip chip bonded onto the surface of the circuit. The electrical connection between the electrode layers 30, 32 of the piezoelectric actuator 26 and the circuit is conveniently achieved via the solder bumps 56 used in the flip chip bonding.

A particular advantage of a switch having a hybrid construction is that the optimum materials and fabrication techniques can be utilised for the cantilever and substrate. For example silicon is an ideal material for the cantilever due to its thermal stability and due to it being inexpensive and readily machinable using micromachining techniques. Although at microwave frequencies silicon is too lossy its effect is minimised by the small area of the contact 24 over which such a signal passes. In contrast GaAs provides an ideal low loss substrate though it tends to be relatively more brittle and difficult to machine. Furthermore the deposition temperature of a piezoelectric thin film, such as PZT, is often greater than the decomposition temperature of GaAs.

A third embodiment of the invention is shown in Figures 7 and 8 which respectively show a membrane switch 60 in an "open" and "closed" configuration. The switch 60 comprises a base or substrate 62, typically of GaAs for microwave operation, carrying a

rectangular frame 64 which circumferentially supports a membrane or diaphragm 66 fabricated of silicon, silicon nitride or silicon oxide. For ease of fabrication the diaphragm 66 is not supported continuously around its periphery and in one embodiment the membrane is secured to the substrate using flip chip solder bonding such that the solder bumps comprise the frame. In another embodiment the membrane comprises a strip supported at opposite ends.

The membrane 66 carries on an upper surface 68 a PZT thin film actuator 70 and on a lower surface 72 a first metal signal carrying line 74. The lower surface 72 and the signal carrying line 74 face the base 62. A second metal signal carrying line 76 is provided on an upper surface 78 of the base. Electrical actuation of the PZT actuator 70 causes the membrane 66 to deform so that it adopts a bowed configuration (as represented in Figure 8) thereby bringing the signal carrying lines 74 and 76 closer together. In this "closed" configuration they are electrically coupled together by capacitive coupling through a dielectric layer 80 present on the second signal carrying line 76. In an alternative arrangement both the signal carrying lines are provided on the substrate and the gap between them is bridged by a corresponding contact on the underside of the membrane. This latter contact arrangement is preferred for switches intended to operate at microwave frequencies since it reduces the switches loss by minimising the surface area of silicon over which the signal passes.

The switches described in the foregoing can be provided as small discrete packaged devices (typically a few millimetres square) or mounted onto microwave circuits prior to packaging. Such micro-switches can be used as broad band switches, for example in the

range d.c to 50GHz. Their simple mechanical action provides low loss (typically less than 0.1dB) and high isolation (for example 50dB at 2GHz and 27dB at 50GHz). A separation between the contacts of 2 μ m in the "open" state is sufficient to achieve isolation of 25dB. Although switches according to the invention have a relatively low
5 switching speed (10 μ s) compared to conventional PIN diode and MESFET switches which can operate as quickly as nanoseconds their speeds are still suitable for a wide range of applications. Piezoelectric actuation requires relatively low drive voltages, typically in the region of 3 to 5V. Such voltages are much lower than those required for electrostatic actuation.

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The switches are suitable for use in phased array systems. They can be used to replace a circulator and provide low loss switching of an antenna connection between a power amplifier in transmission and a low noise amplifier in reception. Such an arrangement is shown in Figure 9. This shows an antenna arrangement used in a phased array system.
15 A common transmit/receive line 90 is connected to two SPST switches 92, 94. The output 96 of the switch 92 is connected to an input of a power amplifier 98 and the output 100 of the second switch 96 is connected to the output of a low noise amplifier 102. Connected to the output of the power amplifier 98 and to the input of the low noise amplifier 102 are respective SPST switches 104, 106. The second connection of each
20 switch 104, 106 is connected to an antenna 108.

Each SPST switch comprises a switch according to the invention as described above. To transmit a microwave signal from the line 92 to the antenna 108, switches 92 and 104 are closed and switches 92, 94 are opened (as shown in Figure 9) thus connecting the

common line 92 to the antenna 106 via the power amplifier 98 whilst isolating the low noise amplifier 102. The states of the switches are reversed to receive a microwave signal from the antenna 108 through the low noise amplifier 102.

5 Alternatively switches according to the invention can be used to switch between short and long transmission lengths to provide a transmission line having a variable length and thus phase delay. An arrangement of about 1000 antenna elements each fed by a track having about five or six sections having different transmission lengths can be used in a phased array system for satellite tracking, for example tracking satellites in a low earth
10 orbit (LEO). Satellite communications typically occur in the region of 18 GHz to 40GHz.

It will be appreciated by those skilled in the art that modifications can be made to the switches described which are within the scope of the invention. For example whilst in
15 the embodiments described the switch is actuated using a piezoelectric material other electro-strictive materials can be used, such as for example PMN:PT (Lead Magnesium Niobate: Lead Titanate). In the context of this patent application an electro-strictive material is a material which undergoes a dimensional change in response to an applied electric field. An advantage of a piezoelectric material is that its change in dimension
20 is substantially linear with applied electric field. It will be further appreciated that multiple layers of electro-strictive material to which opposing polarity electric fields are applied can be used to provide a larger deformation for a given actuating voltage.

Furthermore whilst SPDT switches have been described other forms of switches are

envisaged such as single or multiple double throw switches.

Whilst the switch of the present invention is primarily intended for switching electrical signals it is also envisaged that the switch can be used to switch other media such as for
5 example optical signals. For example in one embodiment the electrically conducting tracks 18, 20 comprise optical waveguides which are fabricated within the substrate 62 and the contact 24 on the cantilever 14 is operable to act as a shutter which is movable into and out of the gap 22, thereby blocking or allowing the passage of light between the waveguides.

CLAIMS

1. An electrical switch comprising: an actuator for moving contacts relative to each other between an open state and a closed state characterised in that the actuator comprises a material which undergoes a dimensional change in response to an electric field applied across the material.
2. An electrical switch according to Claim 1 wherein the material comprises a piezoelectric material.
3. An electrical switch according to Claim 2 wherein the material comprises lead zirconate titanate.
4. An electrical switch according to any preceding claim wherein the actuator comprises a film of said material and two or more electrodes for applying an electric field thereto.
5. An electrical switch according to any preceding claim and further comprising a base carrying one of the electrical contacts and a support member carrying the second contact; wherein the actuator is coupled to said support member such that a dimensional change in the actuator causes a deformation of the support member to open or close the switch.
6. An electrical switch according to Claim 5 wherein the support member is planar

in form.

7. An electrical switch according to Claim 6 wherein the support member is a cantilever.
8. An electrical switch according to Claim 6 wherein the support member comprises a strip supported at opposite edges.
9. An electrical switch according to Claim 5 wherein the support member comprises a membrane.
10. An electrical switch according to any one of Claims 5 to 9 wherein the contact on the base or support member is configured such as to provide an electrical path having a break therein and wherein the corresponding contact on the support member or base is configured to electrically bridge said break when the switch is in a closed state.
11. An electrical switch according to any one of Claims 5 to 10 and further comprising a dielectric layer on one of said pair of contacts such that an electrical signal is capacitively coupled between said contacts when the switch is in a closed state.
12. An electrical switch according to any one of Claims 5 to 11 wherein the support member comprises silicon.
13. An electrical switch according to any one of Claims 5 to 12 wherein the base

comprises gallium arsenide.

14. An electrical switch according to any one of Claims 5 to 13 wherein the support member and the base are fabricated separately and then joined together to provide an assembly.

15. An electrical switch according to Claim 14 wherein the base comprises an integrated surface to which the support member is bonded.

16. An integrated circuit incorporating one or more switches according to any preceding claim.

17. An electrical switch substantially as hereinbefore described or substantially as illustrated by way of reference to any one of Figures 1 to 8 of the accompanying drawings.

17. A phased array antenna incorporating one or more electrical switches according to any preceding claim.

18. A switch designed to be operated by an electro-strictive effect.



Application No: GB 9919435.9
Claims searched: 1 to 18

Examiner: Jason Clee
Date of search: 15 February 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:
UK CI (Ed.R): H1N: NLH
Int CI (Ed.7): H01H: 57/00 & 59/00
Other: Online: WPI, EPODOC & JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB 2169138 A	(General Electric Company) especially see the figures	1, 2, 4-8, 11, 16 & 18
X	GB 2169137 A	(General Electric Company) especially see the abstract and figures 3 & 4	1, 2, 4-7, 10, 11, 14, 15 & 18
X	EP 0189302 A	(NEC Corporation) especially see the abstract and figures	1-3, 5-8 & 18
X	US 4893048 A	(General Electric Company) especially see the abstract and figures	1-7, 10 & 14-18
X	US 4868448 A	(General Electric Company) especially see column 3 lines 21 to 46 and the figures	1-7, 10 & 14-18
X	JP 1130122 A	(Fujikura Ltd) especially see the abstract and figures	18

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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